ASSESSING SIMULATOR SICKNESS IN A SEE-THROUGH HMD: EFFECTS OF TIME DELAY, TIME ON TASK, AND TASK COMPLEXITY

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Abstract

Advances in helmet-mounted displays (HMDs) have permitted the design of "see-through" displays in which virtual imagery may be superimposed upon real visual environments. Such displays have numerous potential applications; however, their promise to improve human perception and performance in complex task environments is threatened by numerous technological challenges. Moreover, users of HMDs may be vulnerable to symptoms associated with simulator sickness. The primary objective of this investigation was to assess subjective ratings of simulator sickness as a function of time delay, time on task, and task complexity. Participants attempted to center a reticle over a moving circular target using a see-through HMD while concurrently performing a visual monitoring task displayed on a computer monitor. Results indicated that simulator sickness ratings varied directly with time on task, while performance efficiency and ratings of perceived mental workload were not mediated by this factor. Furthermore, the time delay manipulation that affected performance efficiency and operator workload did not generally influence SSQ ratings. These findings are discussed in terms of their implications for practical implementation of see-through HMDs in multi-task environments.

Introduction

As described by Durlach and Mavor (1995), advances in helmet-mounted display (HMD) technology have permitted the design of display systems which combine virtual and real environments. Such sytems make use of "see-through" HMDs, which allow virtual imagery to be superimposed upon real visual environments. Indeed, the notion of using see-through HMDs to augment visually-complex real environments is intuitively appealing, and many potential applications have been suggested, including: (1) design, manufacturing, and marketing; (2) medicine and health care; (3) teleoperation for hazardous operations; (4) training; (5) education; (6) information visualization; (7) telecommunication and teletravel; (8) entertainment and art, and (9) national defense (Durlach & Mavor, 1995).

In the case of medical applications, the treatment of tumors by radiation serves as a striking example of how see-through displays may significantly enhance the quality and safety of medical procedures. In short, the goal of radiation treatment is to deliver a high dosage of concentrated radiation to the tumor, while at the same time minimizing the radiation exposure and damage to healthy tissue. However, the patient- and tumor-specific nature of radiation treatment necessitates a methodology that provides exceptional precision. One possibility would be to combine medical imaging technology with see-though visual displays, thus enabling the surgeon to choose the optimal path for the radiation beams and thereby maximizing the dosage of radiation to the tumor while minimizing radiation damage to healthy tissue and organs (see Rheingold, 1991).

A further advantage of augmented display technology is that it may enable surgeons to practice and rehearse surgical procedures, including alternative plans of action in the event of unexpected complications. Again, the idea is to combine see-through HMD displays with information provided by x-rays, magnetic resonance imaging (MRI) scans, and computer tomography (CT) scans so as to enhance the capability of surgeons in the planning and completion of surgical procedures.

With regard to the application of see-through HMDs for tactical aviation, numerous researchers (Adam, 1994; Beal & Sweetman, 1994; Furness, 1986; Wells & Griffin, 1987) have noted the potential tactical advantages. For example, see-through HMDs are capable of displaying flight-critical information irrespective of the pilot's line of gaze, which is consistent with the suggestion of Stinnett (1989) that the ability to "look-around" is advantageous, if not crucial, when

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performing low altitude, terrain-avoidance maneuvers. In addition, see-though display technology may afford all-weather, 24-hour flight operations. Finally, when see-though HMDs are used in combination with targeting-displays, pilots gain the capability to track and designate targets, as well as aim and guide weapons, by line of gaze.

The advantages associated with see-though HMDs may also extend to the design of effective human-machine interfaces for uninhabited aerial vehicles (UAVs). As pointed out in a recent report on UAVs by the United States Air Force Scientific Advisory Board, “the human’s flexibility and capability for inductive reasoning are desirable attributes that justify the retention of a significant supervisory and intervention capability during UAV operations in the foreseeable future” (Worch, 1996, p. 7-2). The latter part of this recommendation implies that there may be situations in which UAV operators are required to assume manual control of certain UAV functions, such as automatic targeting functions and flying/landing the UAV. In these cases, augmented displays may permit UAV ground station operators to perform the additional manual control tasks while concurrently performing their normal ground station monitoring tasks. Moreover, similar to the medical applications, see-through displays may provide UAV ground station operators an effective means for reviewing and rehearsing mission scenarios while the UAV fleet is en route to various tactical destinations.

Despite these advantages, see-through displays are confronted by many technological challenges, including misalignment of virtual imagery with real world objects (Azuma & Bishop, 1994), optical distortion and glare, and problems generic to most HMDs (e.g., helmet fit and discomfort, field of view limitations, suboptimal resolution, and issues involving time delay). Furthermore, while these technical limitations have been shown to adversely affect performance efficiency, control strategies, and operator workload, it is also likely that they occasion the onset of simulation sickness (Kennedy, Lanham, Drexler, Massey, & Lilienthal, 1995). Consistent with this view, Durlach and Mavor (1995) have noted that HMDs increase the likelihood that motion sickness will be a significant problem in synthetic environments, potentially compromising operator safety and acceptance, and thus mission effectiveness.

Simulator Sickness

As defined by Kennedy, Allgood, and Lilienthal (1989), *simulator sickness* refers to

> motion sickness-like symptoms that occur in aircrew during and following training. Symptoms include general discomfort, stomach awareness, nausea, disorientation and fatigue. There is also a prominent component of visually related disturbances such as eyestrain, headache, difficulty focusing and blurred vision ... Aftereffects associated with simulator sickness include postural instability, dizziness, and flashbacks. Flashbacks, which include illusory sensations of climbing and turning, sensations of negative g, and perceived inversions of the visual field, are particularly problematic because of their sudden unexpected onset and risk to safety. (p. 62)

It is important to point out that while the symptomotology of motion sickness and simulator sickness overlap, the pathognomonic signs of the former (i.e., vomiting and retching) are infrequent in the latter (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992). Yet, as noted by Kennedy and his colleagues, the potential for negative aftereffects is one of the most serious problems associated with simulator sickness. Aftereffects associated with flight simulation have included disruptions of postural control (Kennedy, Fowlkes, & Lilienthal, 1993; Kennedy & Stanney, 1996), the illusions of flying and rotating, and the perceived inversion of the visual field (Kennedy et al., 1992).

Besides the untoward effects associated with simulator sickness, Kennedy *et al.* (1992) have suggested that its occurrence may drastically inhibit training effectiveness. For example, in order to reduce symptomatology, operators wearing HMDs may adopt behavioral strategies that are inappropriate for the task at hand, such as closing their eyes, restricting head movement, or looking away from vection-inducing visual displays (Kennedy et al., 1992). Moreover, behaviors acquired to reduce symptomatology may also jeopardize the positive transfer of skills to other VEs or real environments. Paradoxically, extensive training or mission rehearsal with HMDs in which simulator sickness is prevalent may actually impair one’s ability to perform these tasks in the real world.

Hettinger and Riccio (1992) have noted that manifestations of simulator sickness often occur in the presence of excessive time delays, which may cause virtual images to appear to float or swim-around in the HMD, an effect that has been described as subjectively disturbing and nauseogenic (Azuma & Bishop, 1994; Rheingold, 1991; So & Griffin, 1991). While anecdotal evidence seems to support the notion that visual time delays in HMDs play an important role in the occurrence of simulator sickness, research in this area has been sparse. In a recent study addressing the effects of time delay on simulator sickness in a non-see-through HMD, Draper and his colleagues (in review) concluded that reports of simulator sickness did not vary as a function of time delay. These results are consistent with those of Nelson (1996), who found that overall levels of simulator sickness remained unchanged as time delay was increased in a tracking task performed by operators wearing an HMD. Collectively, these studies indicate that time delay may be a necessary but not sufficient condition for the development of simulator sickness.

The purpose of the present experiment was to assess the effects of time delay, time on task, and task complexity on the incidence of simulator sickness in a task performed using a see-through HMD. This extends to a more operationally relevant environment the studies by Draper *et al.* (in review) and Nelson (1996), which were limited by their use of single task environments and non-see-through HMDs. The decision to employ a see-through HMD was motivated by the fact that one of their principal advantages is the ability to support operators in multi-task environments, such as the tracking of virtual imagery while concurrently monitoring events in the real world. Furthermore, Azuma and Bishop (1994) have noted that when see-through displays are used for this purpose in time-delayed augmented realities, virtual objects appear to "swim around" real objects, a condition which may provoke a symptomatology consistent with simulator sickness. These effects may be exacerbated by increased levels of time delay in conjunction with a visually-complex real environment.

Method

Participants

Seven naïve participants, 3 male and 4 female, served in the experiment. Their ages ranged from 20 to 32 years with a mean of 24.35 years. Participants reported normal or corrected-to-normal vision, and indicated that they were not highly susceptible to motion sickness. In addition, all participants reported no prior experience with head-slaved tracking tasks using a see-through HMD. Individuals were paid for their participation.

Experimental Design

A within-subjects design was employed in which two time delay conditions (*nominal*, *nominal + 50 ms*, and *nominal + 100 ms*) were combined factorially with two task conditions (*single* and *dual*) and ten experimental sessions. The single task condition required only the performance of the head-slaved tracking task, while the dual task required participants to perform the tracking task and the monitoring task concurrently. The order of the time delay condition was randomized across participants, while the order of the task conditions was fixed within each session (i.e., blocks of single-task trials preceded the dual-task trials).

Apparatus and Procedure

Each experimental session included 20 5-min head-slaved tracking trials. The first 10 trials served as a baseline condition for head-slaved tracking performance and did not require the participant to perform the visual monitoring task. Trials 11-20 involved both the tracking and monitoring tasks. Prior to the initiation of the main experimental sessions, all participants completed five 5-min practice trials of the secondary visual monitoring task. The purpose of the practice trials was to acquaint participants with the response procedures for the task and to ensure that they were able to perform the task at ceiling level.

Participants used a Kaiser Electronics SimEye 2500 HMD to track a moving visual target. The SimEye 2500 HMD employs an optical relay system to transfer video images from a pair of green phosphor monochrome cathode ray tubes (CRTs) to the participant's eyes. It features a high resolution (1280 x 1024 pixels) binocular display and was configured to provide subjects with a 60° (horizontal) × 40° (vertical) field of view (FOV). The optical focus range of the SimEye 2500 extends from 3.5 feet to infinity, and was set to infinity in the present experiment. The SimEye 2500 weighs approximately four pounds and was configured as a see-through display, thereby allowing participants to view the visual display on which the monitoring task was presented.

The head-slaved tracking task employed target motion patterns (see Fig. 1), or forcing functions, that consisted of the sum of three sine waves with fundamental frequencies of 0.067, 0.117, and 0.233 Hz in azimuth, and 0.083, 0.167, and 0.217 Hz in elevation. Target motions were restricted to ±30° in azimuth, and ±20° in elevation. Different target motions were generated for each trial by randomly assigning phase values at each of the three fundamental frequencies in azimuth and elevation.

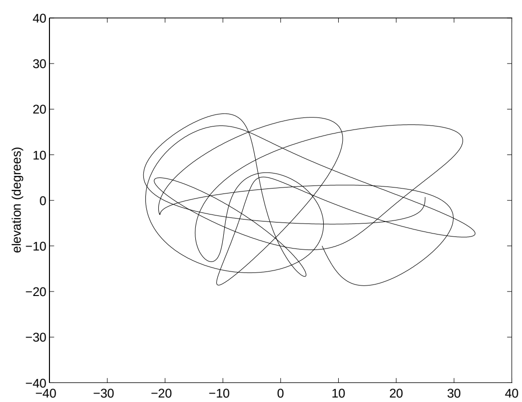

Fig. 1 Example of target motion pattern for the head-slaved tracking task.

Head position and orientation were measured by an Ascension Bird tracker. The Bird consists of a DC magnetic-field transmitter and a receiver that was mounted atop the HMD. The Bird provides six degrees-of-freedom tracking at 120 Hz while minimizing interference caused by nearby metallic objects. All phases of the head-slaved tracking task and data collection were governed by a 200 MHz personal com-

puter. Target and head position data were collected at 60 Hz for each 5-min trial.

The nominal time delay in the head-slaved tracking system was determined to be 46 ms. The imposed time delay conditions consisted of either three or six frames of delay, i.e., 50 or 100 ms, in addition to the nominal time delay.

The secondary monitoring task consisted of the systems monitoring task from the Multi-Attribute Task Battery (MATB; Comstock & Arnegard, 1992). In short, the task comprised a set of four gauges with moving pointers. Under non-signal conditions, the moving pointers oscillated around the center tickmark by no more than one mark from the center tickmark on each of the gauges. A critical signal consisted of any of the four pointers moving more than one mark from the center of the gauge in either direction. Participants were instructed to inspect the gauges for critical signals and to make the appropriate keyboard response as soon as one was detected. Critical signals not detected within 10 s were scored as missed signals; conversely, responses to non-signals were scored as errors of commission. The MATB monitoring task also included a pair of system status displays positioned above the four gauges. The normal or non-signal condition for these displays were the presence of a green light on the left display and a black fill on the right display. Critical signals consisted of the left display shifting from green to black, or the right display shifting from black to red. Again, participants were instructed to inspect the system status display for critical signals and to respond as soon they detected a change in system status. During each of the 5-min experimental trials 12 critical signals were presented – two critical signals for each of the four gauges and two critical signals for each of the system status displays.

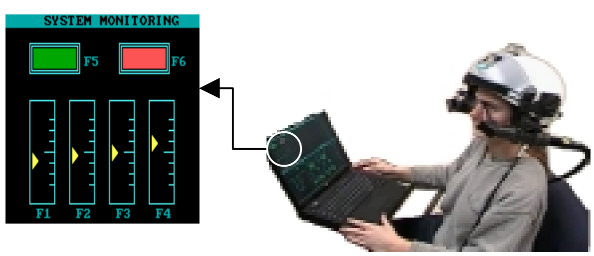

Fig. 2 Participant performing head-slaved tracking task and secondary visual monitoring task.

Upon arrival, participants were presented with an overview of the experimental procedure, received instructions, and donned the HMD. Proper fit and viewing quality in the HMD were achieved by making adjustments to its inter-pupillary distance controls, vertical, tilt, and axial helmet angles, chin strap, variable-thickness foam pads, and inflatable air-bladder. Participants completed 20 5-min head-slaved tracking trials per experimental session – ten trials with and without the additional visual monitoring task (see Fig. 2). Each 5-min trial was preceded by a 5 s target acquisition period to ensure that participants had acquired the target at the onset of the trial. Participants completed the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) at the completion of each 5-min trial and received a 10-min rest period after the completion of five experimental trials. Performance efficiency on the two tasks, as well as the associated workload data, have been presented elsewhere (Nelson, Bolia, Russell, Morley, & Roe, 2000).

Results

Responses to the SSQ were scored according the procedures outlined in Kennedy et al. (1993). Scored in this way, the SSQ yields an overall index of simulator sickness, referred to as Total Severity and three subscales of simulator sickness – Nausea, Oculomotor Disturbance, and Disorientation.

Total Severity Scores

Mean Total Severity scores were submitted to a 3 (time delay) × 2 (task complexity) × 10 (experimental trials) repeated measures analysis of variance (ANOVA), revealing a significant main effect for *experimental trials*, $F(9,54) = 2.30$, $p < .05$, and a significant *task complexity* × *experimental trials* interaction, $F(9,54) = 2.26$, $p < .05$. All other sources of variance lacked significance; however, the *time delay* × *experimental trials* interaction approached significance, $F(18,108) = 1.65$, $p > .05$. The *task complexity* × *experimental trials* interaction, which is illustrated in Fig. 3, can be explained by noting that in the single task condition Total Severity scores increased across trials, but remained invariant across trials under the dual task condition. This impression was confirmed by post hoc test of the simple main effects of trials within the single and dual task conditions, $F(9,54) = 3.18$, $p < .025$, and $F(9,54) = 0.67$, $p > .025$, respectively.

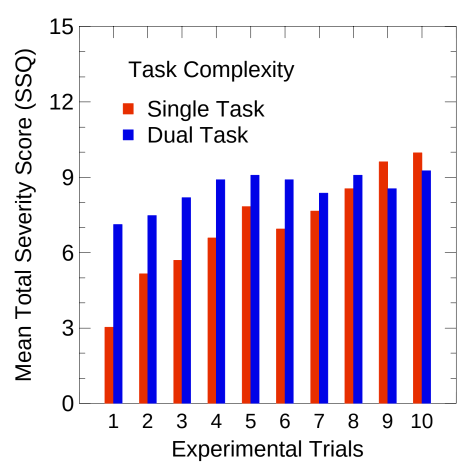

Fig. 3 Mean Total Severity scores as a function of trials under the single and dual task conditions.

Inspection of Fig. 4, which illustrates the *time delay* × *experimental trials* interaction, indicates that the nominal time delay condition was associated with the highest Total Severity scores, and that these ratings generally increased across experimental trials. Further examination of Fig. 4 reveals that the nominal + 100 ms time delay condition resulted in the second highest ratings of overall simulator sickness, but remained relatively stable across experimental trials. It can also be observed in Fig. 4 that the nominal + 50 ms time delay condition was initially associated with the lowest sickness ratings, but eventually increased to a level that was commensurate with the nominal + 100 ms delay condition. A post hoc analysis of these data indicated that the interaction can be explained by noting that sickness ratings varied across experimental trials in the nominal + 50 ms time delay condition, $F(9,54) = 2.67$, $p < .017$, but remained unchanged in the other time delay conditions ($p > .017$, n.s.).

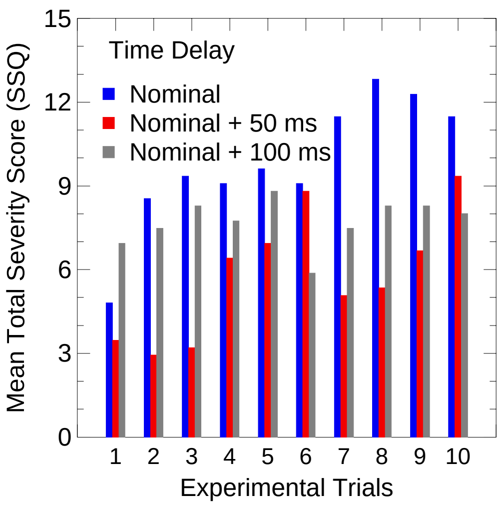

Fig. 4 Mean Total Severity scores as a function trials under the three time delay conditions.

Simulator Sickness Subscale Ratings

The Nausea, Oculomotor Disturbance, and Disorientation data were analyzed by three, 3 (time delay) × 2 (task complexity) × 10 (experimental trials) repeated measures analyses of variance, which indicated main effects for the *experimental trials* factor for both the Nausea (Fig. 5) and Oculomotor Disturbance (Fig. 6) subscales, $F(9,54) = 2.02$, $p < .05$, and $F(9,54) = 3.80$, $p < .05$, respectively, and a *task complexity* × *experimental trials* interaction for the Disorientation subscale, $F(9,54) = 2.10$, $p < .05$. All other sources of variance lacked statistical significance. It can be observed in Fig. 5 that Nausea ratings increased across trials 1-5 and remained relatively constant through trials 6-10. Conversely, inspection of Fig. 6 reveals that Oculomotor Disturbance ratings increased steadily across all experimental trials.

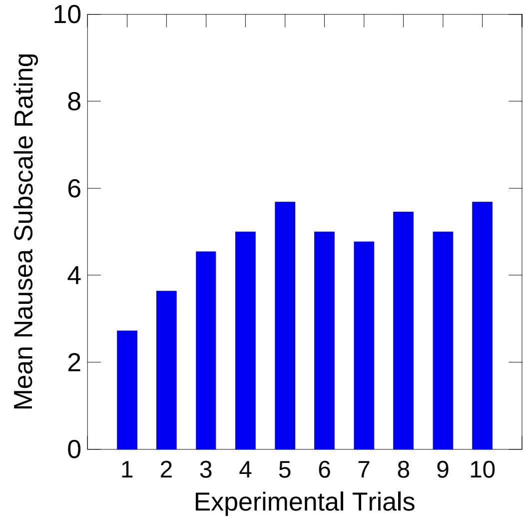

Fig. 5 Mean Nausea subscale ratings across experimental trials.

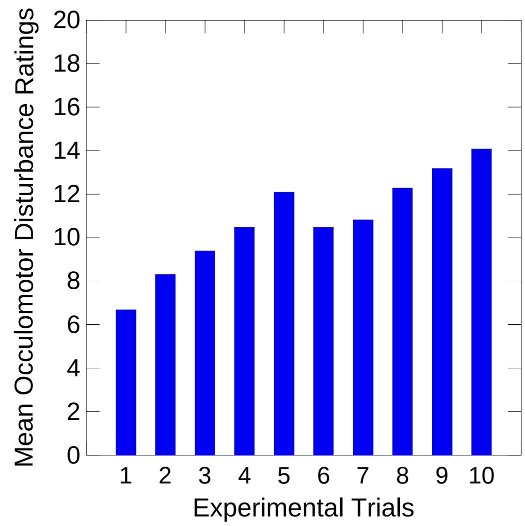

Fig. 6 Mean Oculomotor Disturbance ratings across experimental trials.

Lastly, Fig. 7 illustrates the *task complexity* × *experimental trials* interaction for the Disorientation scores. Perusal of the figure indicates that overall levels of Disorientation were very low throughout most of the experimental trials, with the exception of trial 9 in the single task condition. Post hoc analyses of these data, however, failed to reveal the source of the interaction.

Conclusion

The present study represents an initial effort to evaluate the occurrence of simulator sickness resulting from the effects of time delay, task complexity, and

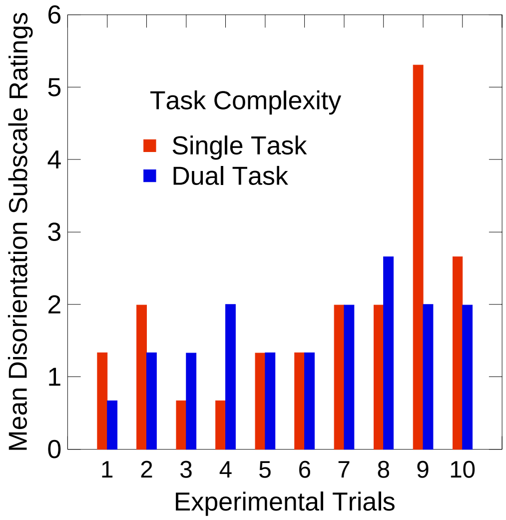

Fig. 7 Mean Disorientation ratings as a function of trials under the single and dual task conditions.

time on task using a see-through HMD. Despite the highly-controlled nature of this experiment, we believe that these results are pertinent to human factors researchers and system designers who are considering the incorporation of see-through HMDs in multi-task work environments.

One of the most striking outcomes of this experiment was the effect of time on task on simulator sickness ratings. Specifically, participants' ratings of Total Severity, Nausea, and Oculomotor Disturbance varied directly with this factor. In addition, the time on task factor was found to interact with task complexity, such that Total Severity scores associated with the single task condition increased across experimental trials, while those associated with the dual task condition remained elevated, but stable. While the profile of Total Severity scores as a function of time on task and time delay was more complex, it too revealed a general trend for increased sickness ratings as time on task increased. Collectively, these results suggest that overall symptoms of simulator sickness were mediated primarily by the time on task factor, and not by time delay or task complexity. This is a surprising outcome given that time delay has been proposed as one of the main etiological factors in the occurrence of simulator sickness in HMDs. This also lends credence to the notion that time delay *per se* is not sufficient for the onset of simulator sickness, a position that has received empirical support from the research of Draper *et al.* (in review) and Nelson (1996).

It is also interesting to view these results in light of reports that symptoms of sickness generally diminish as a function of time spent in flight simulators (Kennedy et al., 1993) and virtual environments employing HMDs (Regan, 1995; Regan & Price, 1994). For example, Regan *et al.* found that participants' ratings of simulator sickness decreased across sessions for each of the SSQ's three dimensions, as well as for the SSQ's Total Severity index. In addition, the largest drops in sickness ratings occurred between the first and second session in the VE, a result that has also be reported by Kennedy et al (1993) for flight simulators. In contrast, the results reported herein indicate that ratings of simulator sickness increased across time. Clearly, further research exploring the effects of time on task on simulator sickness in see-through HMDs is warranted.

What relevance do these findings bear on questions regarding the appropriateness of see-through HMDs for real-world applications? As noted in the introduction, one of the supposed advantages of see-through displays is that they will enable users (e.g., medical students, surgical residents, fighter pilots, etc.) to practice and rehearse the highly precise perceptual-motor skills required by their mission. However, given our finding that reports of simulator sickness increased with time on task, it is unlikely that users would be compelled to spend a sufficient amount of time training and rehearsing mission scenarios. The *time on task* effect also calls into question the efficacy of see-through HMDs for tasks that require operators to use augmented displays for a prolonged amount of time. Such a result may be particularly important for human factors professionals advocating the incorporation of see-through displays in a variety of application domains.

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